Chapter 1: A landscape-based sampling design to assess biodiversity losses from eastern hemlock decline

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INTRODUCTION

In this chapter we describe the development and implementation of a landscape-based, stratified-pair sampling design to analyze differences in aquatic biodiversity between streams draining eastern hemlock (*Tsuga canadensis*) forest stands and those draining hardwood forest stands in Delaware Water Gap National Recreation Area (DEWA). We used geographic information systems (GIS) to assess and summarize landscape variation by forest stand, and statistical analysis to exploit this landscape information by stratifying terrain conditions and pairing similarly structured hemlock and hardwood streams prior to sampling. We found that the stratified pair design effectively reduced terrain influences and highlighted community differences due to vegetation. Use of this methodology allowed us to sample effectively a wide range of conditions while ensuring a balanced design that controlled for landscape variability.

Landscape assessments using GIS techniques are increasingly being used to characterize habitats for wildlife and growing environments for plants. These computerized mapping systems allow for the integration of large amounts of spatial and attribute data over broad areas, providing land managers and scientists with vast amounts of data detailing the variation of environmental parameters such as topography, soils, water resources, and geology (Stow 1993, Burrough 1986). Landscape information can be combined in various ways within a GIS to produce ecologically relevant groupings that can be analyzed for relationships to plant growth, species distribution, or wildlife-habitat interactions (Bailey 1996, Davis et al.1990, Band 1989, Davis and Dozier 1988). Of particular application to fisheries and wildlife studies are techniques for classifying landforms from digital representations of topography that allow an assessment of geomorphologic influences on terrestrial and aquatic habitats (Blaszcynski 1997, Davis and Goetz 1990, Skidmore 1990, McNab 1989, Jenson and Dominque 1988).

Maps of landscape factors can also be exploited in sampling designs to optimize placement of field samples that capture the range of natural variation while minimizing logistical requirements (eg. time and personnel) (Haila and Margules 1996, Gillison and Brewer 1985). When combined with appropriate statistical designs, optimized sample placement using GIS can help to reduce sources of large-scale variation that can confound attempts to determine differences between field samples collected at random locations (Bourgeron et al. 1994, Austin and Heyligers 1989). Uncontrolled spatial sampling schemes may introduce confounding sources of variation (e.g. error) into comparative analyses by selecting sites in different geology, climate, topography, or degree of impact by other types of disturbance. Block, or stratified designs can help to control for sample site variation, as long as relevant environmental information is used to define strata (Bailey 1993). Additionally, pairs of sites within strata can be selected where variance among environmental variables is minimized except for the effect under consideration. This stratified- pair design can help to isolate the effect under consideration and produce stronger comparisons and lead to more relevant inferences.

SETTING

DEWA is located in northeastern Pennsylvania and western New Jersey (Figure 1-1, Inset A). The park encompasses approximately 27,742 hectares of forested hills, ravines, and bottom lands straddling the Delaware River. The park was initially established in 1965 as part of the controversial Tocks Island dam project. While land acquisition and housing relocation was completed in the 1970's, the dam was never constructed and was officially de-commissioned in 1992. Today, abandoned roads and the foundations of many former residences can be found throughout the park. The area surrounding the park is still heavily settled and is a popular resort destination.

Approximately 21,885 hectares of DEWA is forested, of that total approximately 18,575 ha is deciduous forest, 1,295 hectares is evergreen forest, and 2,015 hectares is mixed evergreen-deciduous forest (Myers and Irish 1981). The dominant hardwood species are red oak (*Quercus rubra*), followed by sugar maple (*Acer saccharum*), chestnut oak (*Quercus prinus*), red maple (*Acer rubrum*), and sweet birch (*Betula lenta*). Dominant evergreens are white pine (*Pinus strobus*), eastern hemlock (*Tsuga canadensis*) and red cedar (*Juniperus virginiana*). Although eastern hemlock occurs in nearly pure stands, it also occurs as a significant understory species due to its shade tolerance. Altogether, eastern hemlock occurs as a primary, secondary, or tertiary forest component in approximately 1,130 forested hectares within DEWA (Myers and Irish 1981). Because the focus of this study was eastern hemlock, we defined an eastern hemlock stand as comprising either the primary, secondary, or tertiary forest component.

The physical setting of DEWA is varied with terraced benches and ravines to the east, significant river bottom habitats surrounding the Delaware River, and steeply sloping ridge habitats to the west. Minimum elevation is approximately 84 meters and maximum elevation is approximately 490 meters. Approximately 60 kilometers of the Delaware River flow through the park. Additionally the park has some 87 kilometers of 1st order streams, 32 kilometers of 2nd order streams, and 60 kilometers of 3rd or higher order streams, many of which originate outside the park.

METHODS

<u>Map analysis</u>
We used GIS to develop and manage landscape data and to create landscape-based strata used for the stratified-pair design. We developed sampling strata that captured environmental factors (vegetation, terrain, and stream size) deemed to have importance in structuring aquatic communities. Since the basis for our aquatic community comparisons would be vegetation

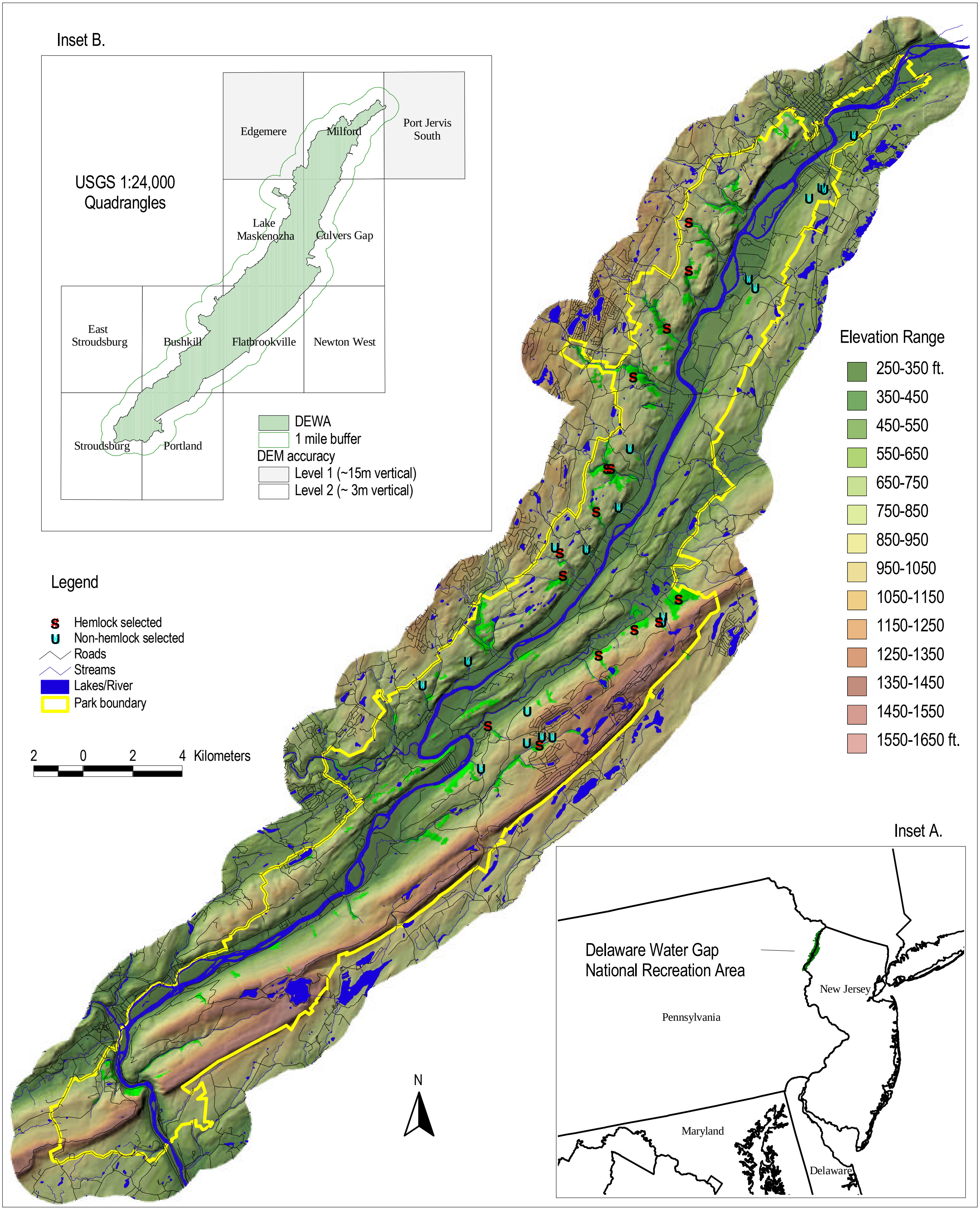


Figure 1-1. Delaware Water Gap National Recreation Area (DEWA) depicting terrain (as shaded elevation), location of hemlock stands (bright green), road systems, and stream drainaiges. USGS 1:24,000 quadrangles used as basis for modeling are shown in Inset A. Location of Delaware Water Gap NRA depicted in Inset B.

differences (i.e. hemlock versus hardwood forests), we used a digital vegetation map to classify land cover types and separate eastern hemlock forests from other forest types. Terrain has an important role in structuring aquatic communities by regulating energy and allochthonous inputs such as temperature and moisture patterns, incident light, and delivery of soil and plant materials to streams (Frissell et al. 1986, Cummins 1992). We characterized terrain by deriving measures of elevation, slope, aspect, shape, and shade from a digital terrain model. Lastly, because stream size and position in the drainage network strongly influence aquatic community structure (Minshall et al. 1985, Osborne and Wiley 1992), we characterized stream size (order) and length using a digital stream map.

DEWA personnel provided digital GIS coverages of vegetation, roads, streams, and boundaries. Vegetation was mapped from 1:12,000 aerial photographs by DEWA personnel in the early 1980's (Myers and Irish 1981). Vegetation is grouped into "stands" or polygons of similarly structured plant composition on this map; each stand is coded with cover type, species composition, and crown closure. Because the vegetation map contained non-forest vegetation components (eg. grasses, herbaceous plants, agriculture, etc.) as well as forest components, we created a new file containing only forest polygons to use in subsequent analysis. In addition, we divided polygon boundaries for forest stands into separate files for hemlock and non-hemlock forests. The vegetation map defined primary, secondary, and tertiary vegetation composition for each stand, reflecting the dominance by canopy area in each species. Because effects on hemlock were of interest, we placed stands with hemlock defined as either the primary, secondary, or tertiary component into a hemlock stand file (N=142 stands). All other forest stands were placed into a separate non-hemlock forest stand file (N=2145).

After initial polygon selection, we converted all GIS maps to a grid representation where geographic space is divided into a matrix of equal size cells of a given ground distance. In this grid or "raster" representation, each cell is tagged with an attribute (eg. elevation, forest type, etc.), and a stand is represented as a collection of cells with identical attributes. We used a cell size of 30 meters ground distance for compatibility with existing digital elevation maps used for terrain modeling. We conducted subsequent analyses using both the grid and polygon representations of forest stands (and other GIS files); the map representation used depended on the requirements of a particular analysis task and the tools available in Arc/Info (ESRI, Inc.: Redlands, CA).

We merged 10 U.S. Geological Survey 1:24,000 Digital Elevation Model (DEM) files together using Arc/Info to form a seamless elevation map for DEWA. In these files, elevations are recorded at regular intervals (as meters above sea level) at points separated by 30 meters ground distance. Conversion of these files into a GIS layer creates a regular grid of elevations with one elevation value per cell. Vertical accuracy of these files is reported to be " 3 meters for 8 of the 10 DEM files and " 15 meters for 2 of the DEM files (USGS, 1995). Differences in accuracy reflect mapping methodology used to record elevations from source materials (USGS, 1995). Due to the orientation of the park boundary in relation to the DEM files, the lower accuracy files affected only small portions of the study area (Figure 1-1, Inset B).

We created a subset of the elevation grid using GIS by Aclipping@ the grid to an area defined by a 1 mile buffer from the park boundary. This defined a digital terrain model whose boundary corresponded to digital data layers supplied by DEWA personnel. All other terrain variables were derived from this digital terrain model. Since the digital terrain model records elevations directly, no additional processing was needed to define the elevation layer (Figure 1-1). We derived the remaining terrain variables from the elevation layer using various algorithms available in the Arc/Info software package (ESRI, Inc. Redlands, CA).

Aspect was generated from the digital elevation model by measuring the direction of the maximum rate of change (slope) calculated for a 3x3 window surrounding each cell (ESRI, Inc. 1994). The output of the aspect function is a compass bearing from 0-359 degrees for each cell. In order to make this measure useful in multivariate analysis, aspect was translated to a measure of Anorthness@ by a cosine transformation so that aspect varies continuously from -1 (south) to 1 (north) (S. Weiss, Standford Univ., pers. comm.)(Figure 1-2a.).

Slope (percent) was generated from the elevation matrix for each cell and measures the maximum rate of change in elevation from each cell to its neighbors (ESRI, Inc. 1994) (Figure 1-2b.). Conceptually, a plane is fitted over a 3x3 window of cells surrounding the cell of interest and the slope of the plane is calculated (Burrough 1986).

A measure of relative incident light striking the surface was calculated from the digital elevation model using the Ahillshade@ function in Arc/Info. This function allows for calculation of surface areas in direct sunlight, shade, and shadow given the elevation and azimuth of a light source (e.g., the sun). We calculated the sun=s position and height above the horizon at the summer and winter solstice for our study area using tables provided by Marsh (1983). A mean relative solar radiance value was calculated by taking the by-pixel mean of these two surfaces. This calculated grid provided a measure of mean solar illumination during the year at each pixel relative to other pixels on the surface (values range from 0-255, are relative to the map, and do not reflect actual light reaching the surface)(Figure 1-2c.).

A measure of terrain shape was calculated from the digital elevation model following methods outlined in McNab (1989). The Aterrain shape index@ quantifies local convexity or concavity of a terrain surface. This measure is calculated using GIS as the difference between elevation at the center of a “moving window” and surrounding cells in the window. A moving window is generated by measuring attributes of a cell in relation to its neighbors in a matrix of cells; the next cell to the right is then processed in relation to its neighbors, and so forth. By varying the size of the window used to calculate the index, different scales of convexity and concavity can be measured. We used a circular moving window of 150m radius (5 cells on the DEM) to calculate terrain shape. We chose this window size after experimentation because it captured the prominent features at the scale of interest for our study area such as ravines and bench environments. Negative terrain shape values indicate a locally concave surface (e.g. a ravine) while positive values indicate a locally convex surface (e.g. a ridge or hummock). Values near zero indicate a locally flat surface (Figure 1-2d.).

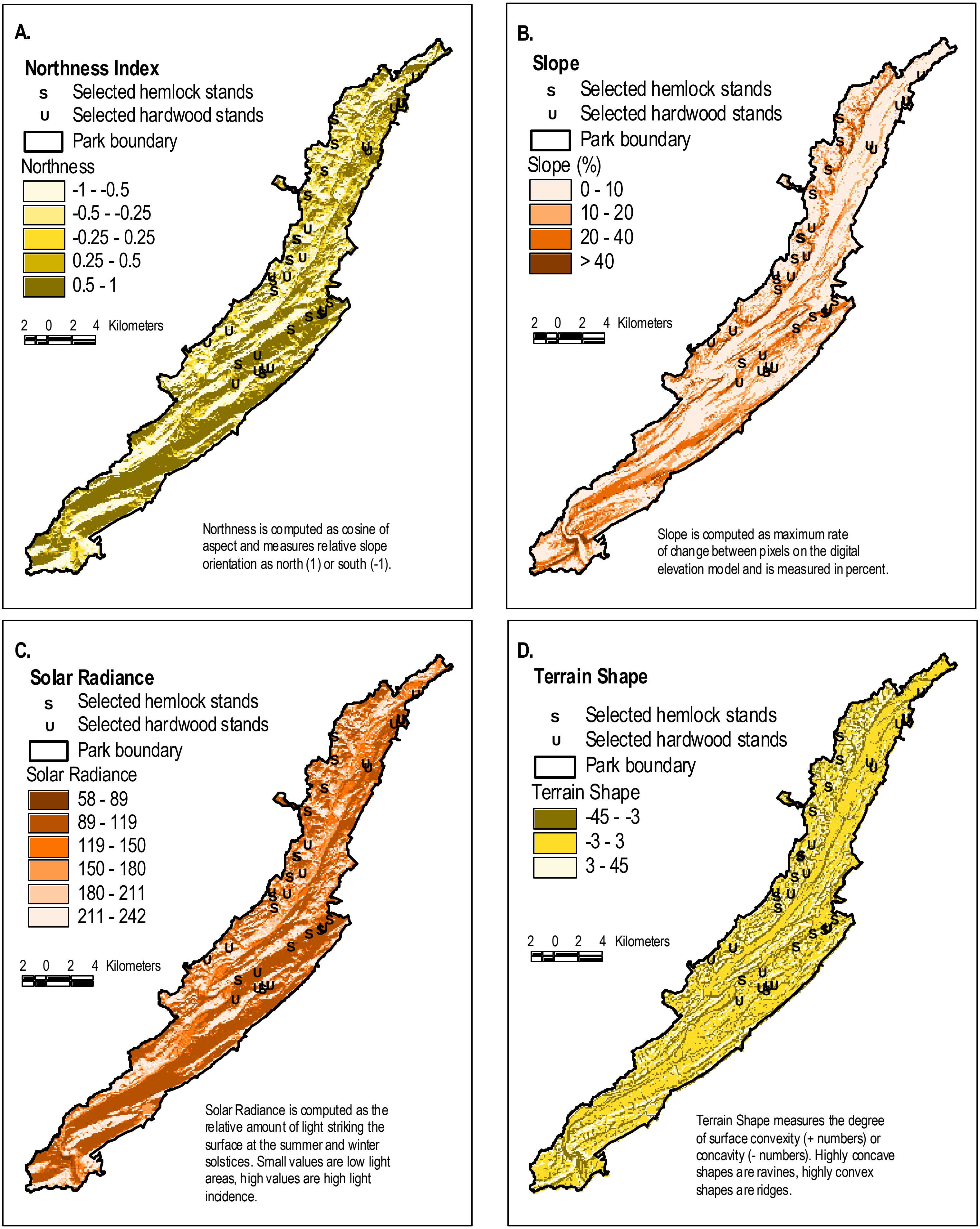


Figure 1-2. Terrain variables for Delaware Water Gap National Recreation Area used in sample design. Also shown are selected hemlock and non-hemlock study site locations.

We computed summaries of the elevation, slope, northness, terrain shape, and solar radiance terrain variables for all forest stands. This was accomplished using map overlay techniques to summarize the by-pixel terrain variables within each of the forest stand boundaries. Statistical summaries of the mean, variance, and range of pixel values were computed for each stand. We standardized the terrain variables to mean zero and unit variance by calculating z-scores for each of the terrain variable maps to eliminate bias due to different measurement units (Freund 1981).

Roads and streams were mapped by the US Geological Survey, National Mapping Division at 1:24,000 map scale. We augmented the stream map by calculating stream order for major tributary stream systems flowing into DEWA using the Strahler method (Strahler 1964).

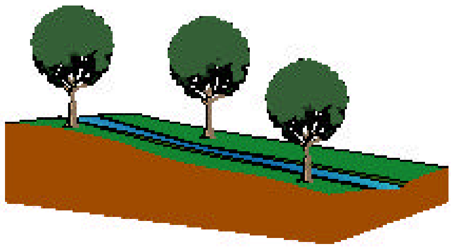
Statistical clustering and stratification

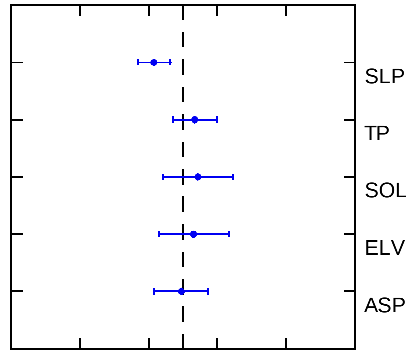
We used terrain variables described above to examine the range of environmental conditions where hemlock trees are found, and to determine terrain types that could be used to stratify field sampling. We used Euclidean distance-based K-means clustering in Systat (Wilkinson et. al 1998) to determine terrain types among 142 hemlock stands using 5 terrain variables.

We initially clustered hemlock stands into 3-10 strata. Upon examination of profile plots and cluster means of terrain variables, we reduced the number of strata to 3. This provided easily interpretable groups of hemlock environments that captured the main terrain types where hemlock occurs in DEWA: ravine, bench, and mid-slope (Figure 1-3). The Aravine@ type represents large, generally northwest trending, topographically concave drainages. The Abench@ type represents gently sloping, topographically flat to slightly convex areas at moderately high elevations. The Amid-slope@ type represents low incident light, steeply sloped, topographically convex areas that generally occur in the mid-slope regions of hillsides in the park.

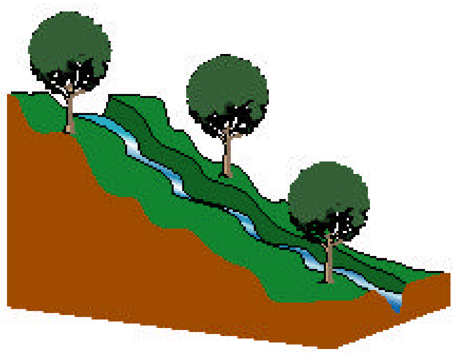
To test for differences in biota based on vegetation, we needed to control for differences in two factors thought to be important for structuring aquatic communities: stream order and terrain. Thus, the overall design called for construction of a 2x2x3 block matrix based on two vegetation strata (hemlock forest/non-hemlock forest), 2 stream order strata (1st order/ 2nd order), and 3 terrain strata (bench/ravine/mid-slope) (Table 1-1). We used the stand-based vegetation map to construct 2 vegetation strata by classifying forest type as either hemlock or non-hemlock. We created 2 stream order strata by computing stream order for all streams within DEWA (described above) and intersecting the stream and vegetation maps in GIS using a map overlay technique. We then selected only those hemlock (N=56) and non-hemlock (N=333) forest stands from the vegetation map that were drained by 1st or 2nd order streams. The bench, ravine, and mid-slope terrain strata were constructed using clustering on 5 terrain variables as previously described.

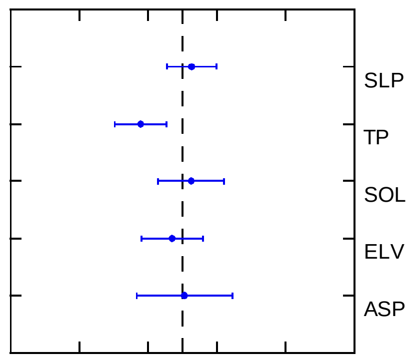
We defined 5 overall strata by combining terrain type and stream order. We were unable to completely fill the 2x2x3 sampling matrix as one of the terrain strata (Amid-slope@) did not contain streams of greater than 1st order. Combined terrain type/stream order strata (hereafter termed simply "stream types") were assigned designations as follows: bench, stream order 1;



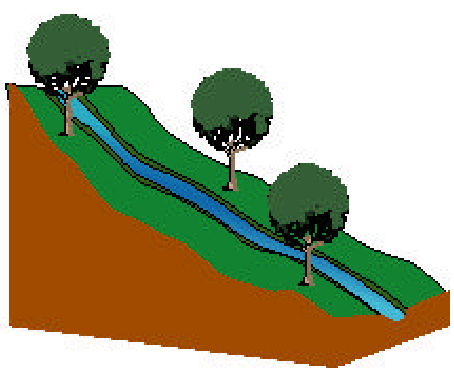


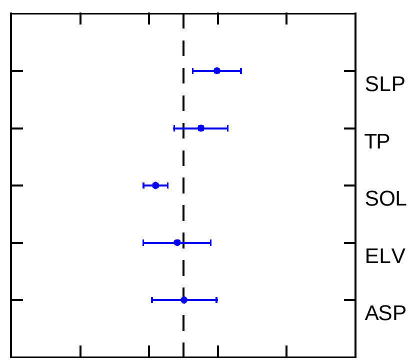
Bench sites - Low gradient, topographically flat to slightly convex areas with moderately high elevation





Ravine sites - Moderate to high gradient, topographically concave areas at lower elevations.





Mid-slope sites - Very steep, topographically convex areas with low light.

Fig. 1-3. Conceptual diagram of the 3 terrain strata sampled in DEWA (left) as defined by cluster analysis. Cluster profile plots (right) show the distribution of five topographical variables used in cluster analysis (SLP=slope, TP=terrain shape, SOL=solar radiance, ELV=elevation, and ASP=aspect). Dotted lines in cluster profile plot indicate the grand mean for each variable, circles indicate the within-cluster mean, and horizontal line indicates one standard deviation above and below the mean. Stream order was also considered as a criterion in selecting and pairing stream sites.

bench, stream order 2; ravine, stream order 1; ravine, stream order 2; mid-slope, stream order 1).

Table 1-1. Terrain and stream order strata defined for the landscape-based sample design, and number of replicate sample sites placed in each strata. Hemlock and hardwood sites in similar strata were paired for analysis to minimize influences from terrain and stream size. No mid-slope, stream order 2 sites were present on the landscape. One bench, second order pair was dropped during sampling *.

	Hemlock		Hardwood	
Terrain strata	*Stream order 1*	*Stream order 2*	*Stream order 1*	*Stream order 2*
Bench	3	3 *	3	3 *
Ravine	3	3	3	3
Mid-Slope	3	N/A	3	N/A

Within each of the resulting strata, we used a multivariate pairing method to find similar pairs of hemlock and non-hemlock stands. Our goal was to find pairs of stands where stream order was equivalent and differences between terrain variables were minimized, thus allowing us to observe differences in stream biota with "all else being equal", to the extent possible. Stand pairing was accomplished by computing a multivariate Euclidean distance in S-Plus (Venables and Ripley 1994) between all possible pairs of hemlock forest stands and non-hemlock forest stands using mean terrain variables (elevation, slope, northness, terrain shape, and relative solar radiance) measured for each stand and summarized as z-scores. We sorted distances in ascending order and selected the 10 closest non-hemlock matches for each input hemlock stand. We then assessed each selected hemlock stand against the 10 potential hardwood matches for viability as matched pairs.

After generating lists of matched pairs of hemlock and non-hemlock forest stands within each combination of stream order and hemlock cluster, we met with park personnel to evaluate the feasibility of sampling each stand pair based on logistics and sampling considerations. These included access, stand size (only stands greater than 5 ha were selected), influence of human disturbance, beaver activity, other forest types upstream of the stand, and length of stream within the stand available for aquatic sampling. Using the generated list of paired stands, we were able to quickly find appropriate matched pairs that could be accessed by field crews and were similar in terrain and stream order, but different in vegetation type. Field inspection confirmed the strength of site similarity based on terrain, and led to selection of 15 pairs for sampling. One pair was discarded (bench, stream order 2) during Spring 1997 sampling due to clear differences in water flow. Timber cruises were also conducted in selected stands by personnel from Pennsylvania State University to assess vegetation composition and to check the accuracy of vegetation maps (Sullivan et. al. 1998).

RESULTS

Statistical summaries of elevation, slope, "northness", terrain shape, and solar radiance computed for all forest stands (Table 1-2) show that hemlock stands generally occur in a lower elevation, higher slope, lower light environments ("northness" and relative solar radiance), and in more concave terrain shapes than hardwood forests. This finding is in line with expectations that hemlock occurs in more shaded environments, and persists in areas that were less accessible to past harvest activities. In general, selected forested stands had less within forest type terrain variance than among the overall population of hemlock and hardwood stands.

Table 1-2. Distribution of terrain variables among vegetation types within Delaware Water Gap National Recreation Area.

Forest type	Terrain variable	Minimum	Maximum	Range	Mean	Std. dev.
All hemlock	Elevation (m)	88.00	422.00	334.00	203.08	55.37
All non-hemlock	Elevation (m)	85.00	490.00	405.00	203.07	125.02
Selected hemlock	Elevation (m)	120.00	375.00	255.00	220.03	45.83
Selected non-hemlock	Elevation (m)	108.00	379.00	271.00	248.70	65.79
All hemlock	Slope (%)	0.00	99.39	99.39	25.82	16.99
All non-hemlock	Slope (%)	0.00	147.58	147.58	15.70	14.96
Selected hemlock	Slope (%)	0.59	87.90	87.31	26.13	15.69
Selected non-hemlock	Slope (%)	0.00	77.25	77.25	18.51	11.78
All hemlock	Northness index	-1.00	1.00	2.00	0.33	0.64
All non-hemlock	Northness index	-1.00	1.00	2.00	0.08	0.66
Selected hemlock	Northness index	-1.00	1.00	2.00	0.26	0.62
Selected non-hemlock	Northness index	-1.00	1.00	2.00	0.21	0.68
All hemlock	Relative solar radiance	58.00	241.50	183.50	129.89	44.64
All non-hemlock	Relative solar radiance	60.50	241.50	181.00	128.23	69.65
Selected hemlock	Relative solar radiance	73.00	241.00	168.00	132.85	41.77
Selected non-hemlock	Relative solar radiance	79.00	241.50	162.50	141.77	46.11
All hemlock	Terrain shape	-42.93	28.43	71.36	-2.24	8.36
All non-hemlock	Terrain shape	-39.09	44.41	83.49	0.42	5.18
Selected hemlock	Terrain shape	-34.30	21.72	56.01	-3.12	8.71
Selected non-hemlock	Terrain shape	-28.99	16.93	45.91	-0.56	5.28

Discriminant analysis conducted on hemlock stands clustered into terrain strata confirmed the strength of group membership (Table 1-3). Discriminant analysis tests the separation of observations into previously defined groups and can be used as a check on multivariate classification (Davis, 1986). Overall classification accuracy was 99 percent, with only two stands out of 142 mis-classified. This result confirms that terrain strata were strongly defined. An evaluation of the matched hemlock and hardwood stands revealed that, on average, hemlock stands were more similar in terrain to matched hardwood stands than to other hemlock stands grouped in the same terrain strata. Multivariate distances generated between hemlock stands and matched hardwood stands were generally smaller (i.e. more similar) when compared to multivariate distances computed among hemlock stands within the same terrain strata (see example in Figure 1-4).

Table 1-3. Results of discriminant function test on hemlock stand clusters showing strength of group membership. Table shows observations classified from cluster analysis (rows), predicted group membership based on discriminant function test (columns), and between group F statistic in parentheses. Only two observations were predicted to be in classes other than those assigned from clustering. Overall classification accuracy was 99 percent.

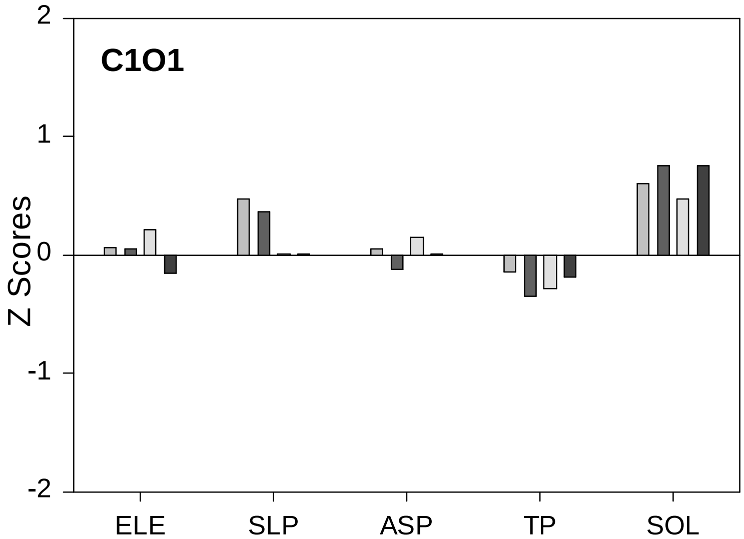
	Predicted Group Membership			
Terrain Strata	***1 (bench)***	***2 (ravine)***	***3 (mid-slope)***	***%correct***
1 (bench)	62 (0.0)	0 (32.309)	1 (50.955)	98
2 (ravine)	0 (32.309)	35 (0.0)	1 (37.998)	97
3 (mid-slope)	0 (50.955)	0 (37.998)	43 (0.0)	100
Total	62	35	45	99

Sites selected and sampled for aquatic macroinvertebrates and fish are shown in Figure 1-6 . Additionally, automated temperature loggers were placed in a subset of sites and retrieved after 1 year of hourly data collection (discussed fully in Chapter 4). Locations of temperature loggers are shown graphically in Figure 1-6. Coordinates, site numbers, stream name, and site pairs for all sites sampled for macroinvertebrates and fish are listed in Appendix 1-A.

DISCUSSION

The landscape-based stratified-pair design was successful in representing the range of terrain variation in DEWA and in minimizing the confounding influence of landscape variation between paired sites. Terrain variable means were not markedly different between 14 selected hemlock stands and the 127 non-selected hemlock stands (Figure 1-5), or between 14 selected non-hemlock stands and the 2,131 non-hemlock forest stands left unselected (Figure 1-5). Overall terrain variable distributions show greater ranges than the stands selected for sampling, due primarily to stands found on ridge tops or near river bottoms that would have been logistically difficult to sample.

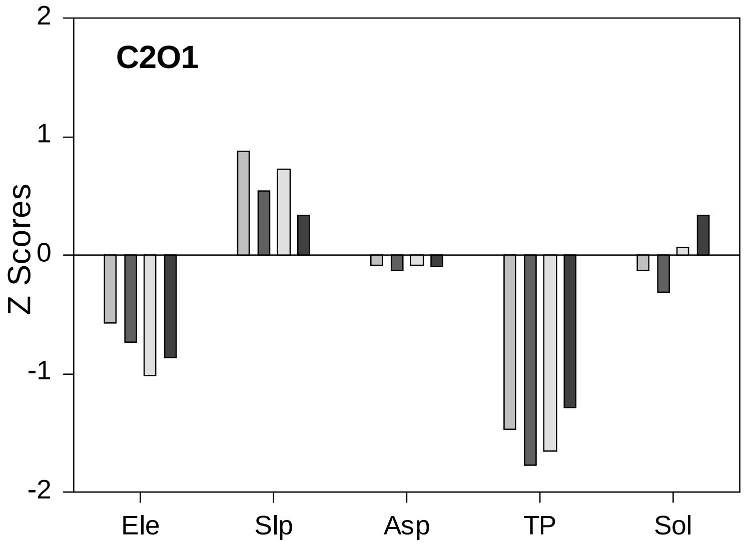
Because this sampling design is meant to highlight differences in aquatic systems due to vegetation differences, the accuracy of vegetation information used to select stands is important. Data collected by Pennsylvania State University (Sullivan et. al. 1998) in stands we selected



Stnd #	Dist	Area	Stream
S2037	**NA**	**82598**	**268**
S1523	0.31	122391	201
S1901	0.37	206664	449
S529*	0.30	25744	744

Hemlock Distance Summary

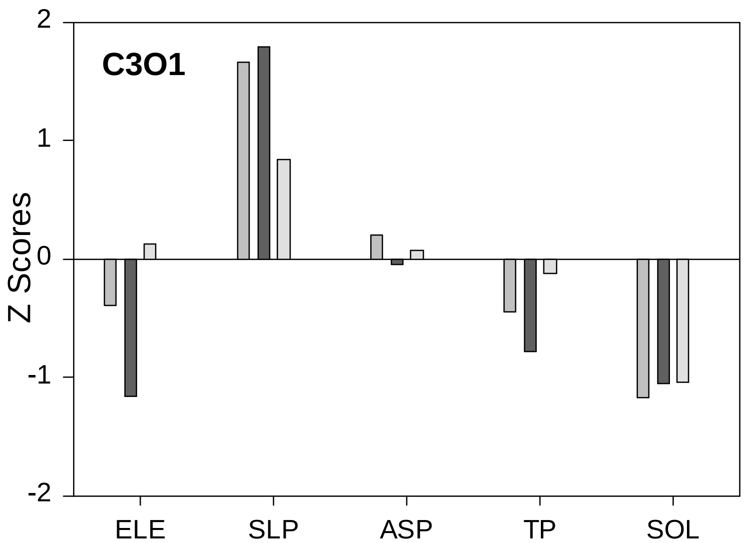
Mean = 1.46
Median = 1.46
Min. = 0.33
Max. = 2.74



Stnd #	Dist	Area	Stream
S1449	**NA**	**159366**	**1039**
S1672	0.51	64173	448
S1202*	0.54	86458	289
S1260	0.79	85222	354

Hemlock Distance Summary

Mean = 1.77
Median = 1.86
Min. = 0.38
Max. = 3.01



Stnd #	Dist	Area	Stream
S1673	**NA**	**61784**	**255**
S2109	0.86	111866	103
S1614*	1.03	432271	354

Hemlock Distance Summary

Mean = 1.05
Median = 0.98
Min. = 0.50
Max. = 1.54

Figure 1-4. Examples of multivariate dissimilarity scores for hemlock (H) and closest non-hemlock (N) stands on terrain variables for selected terrain/stream order strata. Mean dissimilarity scores were generally lower (i.e., more similar) between selected hemlock-hardwood site pairs (top table - selected hardwood site with asterisk) than among hemlocks within the same terrain/stream order strata (bottom table).

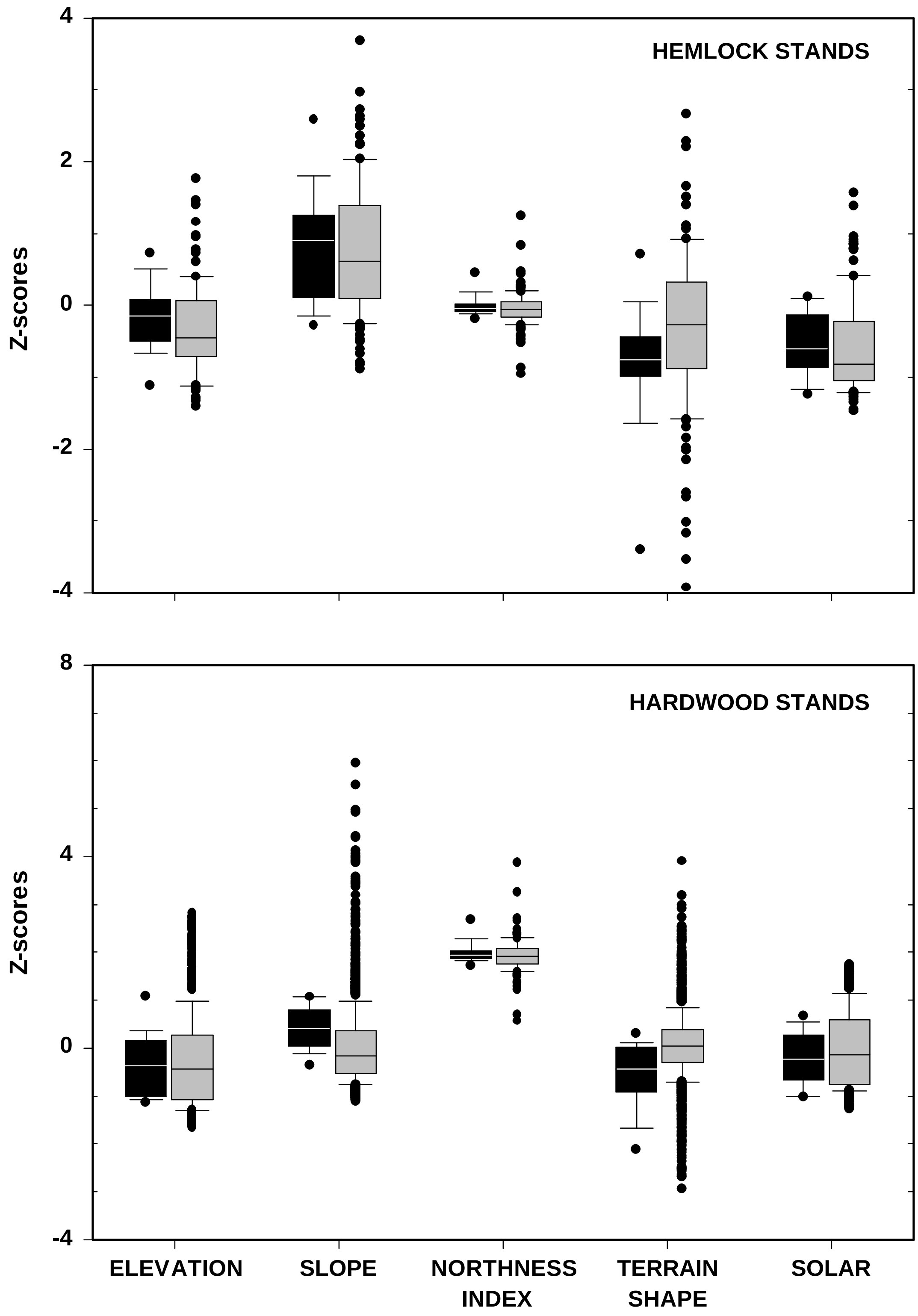


Figure 1-5. Comparisons of the distributions of the five terrain variables between selected (black boxes) and non-selected (gray boxes) stands. Top panel compares hemlock stands and bottom panel compares hardwood stands. Boundaries of the box mark the 25th and 75th percentile, the line within the box marks the median, and the whiskers mark the 10th and 90th percentiles. Symbols represent values lying outside the 10th and 90th percentiles.

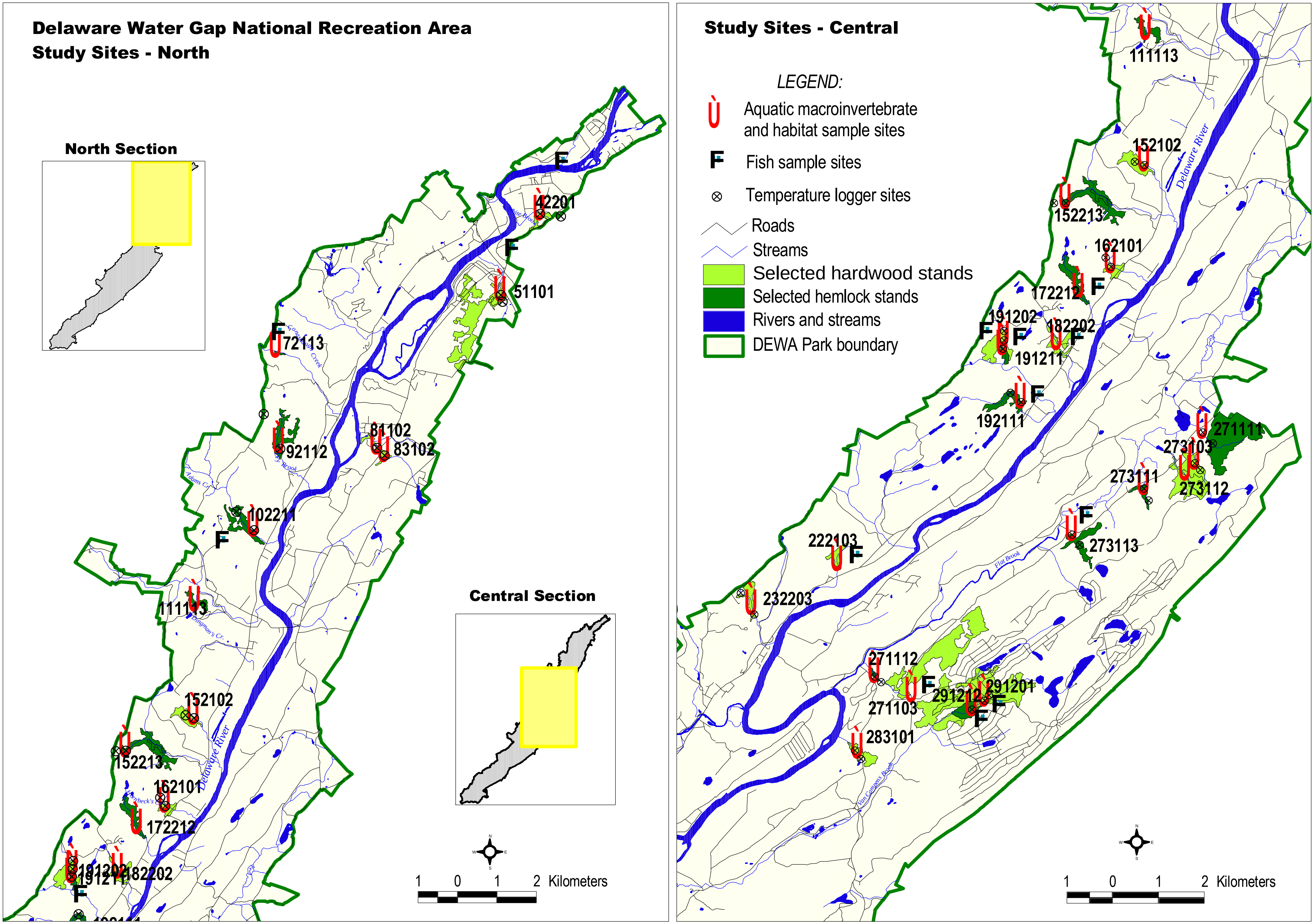


Figure 1-6. Graphic depiction of study sites sampled in DEWA showing macroinvertebrate and fish sampling locations, temperature logger placement, selected forest stand boundaries, and streams. 28 sites were sampled, primarily in the north (left) and central (right) sections of the park.

demonstrates that vegetation composition was consistent with the *a prior* classification from vegetation maps produced by Myers and Irish (1981). Since we defined a hemlock stand as containing hemlock in either the primary, secondary, or tertiary forest component, we expected to have mixed composition stands in our analysis. Results from Sullivan et. al. (1998) indicate that stands classified as hemlock contained at least 24% basal area in hemlock and as much as 75% hemlock; typically, hemlock classified stands had 53% basal area in hemlock. Furthermore, the amount of hemlock in hemlock stands was consistently greater than its hardwood stand pair. The amount of hemlock basal area in a stand classified as hemlock was between 2 and 27 (and typically 13) times that of its hardwood stand pair (Sullivan et. al 1998).

Although this sampling scheme is based on classical sampling designs (e.g. randomized blocks), it incorporates aspects of more recent designs as well. This design allows for inclusion of landscape variation measured through use of GIS (sensu "gradsect" sampling: Gillison and Brewer 1985), as well as pairing to control for possible confounding variables (sensu case-control sampling; Schlesselman 1982). First, we used easily obtainable *a priori* information on terrain and vegetation to characterize hundreds of hemlock and non-hemlock forest stands within the park. Then we used this characterization to define landscape-based strata and to match pairs of hemlock and hardwood stands before field sampling. Evaluation demonstrates that this methodology was successful in capturing the range of terrain conditions in the park (Figure 1-5), in defining ecologically meaningful sampling strata (Table 1-3), and in finding closely matched hemlock-hardwood pairs (Figure 1-4). Subsequent chapters evaluate whether the design was ultimately successful in controlling confounding variation in observed aquatic community differences.

LITERATURE CITED

Austin, M.P. and P.C. Heyligers. 1989. Vegetation survey design for conservation: Gradsect sampling of forests in north-eastern New South Wales. Biological Conservation. Vol. 50. pp. 13-32.

Bailey, N.T. 1995. Statistical Methods in Biology, Third Edition. Cambridge University Press. Cambridge, Great Britain. 255 pp.

Bailey, R.G. 1996. Ecosystem Geography. Springer-Verlag, New York. 204 pp.

Band, L.E. 1989. Automating topographic and ecounit extraction from mountainous forested watersheds. AI Applications. Vol. 3, No. 4.

Blaszczynski, J.S. 1997. Landform characterization with geographic information systems. Photogrammetric Engineering and Remote Sensing. Vol. 63. No. 2. pp. 183-191.

Bourgeron, P.S., H.C. Humphries, and M.E. Jensen. 1994. General sampling design considerations for landscape evaluation. In Eastside Forest Ecosystem Health Assessment, Volume II: Ecosystem Management and Principles, M.E. Jensen and P.S. Bourgeron, eds. US Department of Agriculture, Forest Service, General Technical Report PNW-GTR-318. pp. 109-120.

Burrough, P.A.1986. Principles of Geographical Information Systems for Land Resources Assessment. Oxford University Press, New York.

Cummins, K.W. 1992. Catchment characteristics and river ecosystems. Pages 126-135 In: P.J. Boon, P. Calow, and G.E. Petts (editors). River Conservation and Management. Wiley Publishers, West Sussex, England.

Davis, F.W., D.M. Stoms, J.E.Estes, and J. Scepan. 1990. An information systems approach to the preservation of biological diversity. Int. J. Geographical Information Systems. Vol. 4, No. 1. pp. 5-78.

Davis, F.W. and Goetz, S. 1990. Modeling vegetation pattern using digital terrain data. Landscape Ecology. Vol. 4, No. 1. pp. 69-80.

Davis, F.W. and Dozier, J. 1988. Information analysis of a spatial database for ecological land classification. Photogrammetric Engineering and Remote Sensing, Vol. 56, No. 5. pp. 605-613.

Davis, J.C. 1986. Statistics and Data Analysis in Geology. John Wiley & Sons. New York. 646 pp.

Environmental Systems Research Institute (ESRI), Inc.. 1994. Documentation for ArcInfo Software, Version 7.0. Redlands, CA.

Freund, J.E. 1981. Statistics: A First Course, 3rd Edition. Prentice-Hall, Inc. Englewood Cliffs, New Jersey. 466 pp.

Frissell, C.A., W.J. Liss, C.E. Warren, and M.D. Hurley. 1986. A heirarchical framework for stream habitat classification: Viewing streams in a watershed context. Environmental Management. Vol 10. pp. 199-214.

Gillison, A. N. and K.R.W. Brewer. 1985. The use of gradient directed transects or gradsects in natural resource surveys. Journal of Environmental Management. Vol. 20. pp. 103-127.

Haila, Y. and C.R. Margules. 1996. Survey research in conservation biology. Ecography. Vol. 19. pp. 323-331.

Jenson, S.K. and J.O. Dominque. 1988. Extracting topographic structure from digital elevation data for geographic information system analysis. Photogrammetric Engineering and Remote Sensing. Vol. 54, No. 11. pp. 1593-1600.

Marsh, W.M. 1983. Landscape Planning: Environmental Applications. John Wiley and Sons. New York. 356 pp.

Minshall, G.W., R.C. Petersen, Jr., and C.F. Nimz. 1985. Species richness in streams of different size from the same drainage basin. The American Naturalist. Vol 125. pp. 16-38.

Myers, W.L. and R.R. Irish. 1981. Vegetation survey of Delaware Water Gap National Recreation Area. Final Report, USDI National Park Service, Mid-Atlantic Region.

Osborne, L.L. and M.J. Wiley. 1992. Influence of tributary spatial position on the structure of warmwater fish communities. Canadian Journal of Fisheries and Aquatic Sciences. Vol. 49. pp. 671-681.

Schlesselman, J.J. 1982. Case-control studies. Oxford University Press, New York.

Skidmore, A.K. 1990. Terrain position as mapped from a gridded digital elevation model. Int. J. Geographical Information Systems. Vol. 4, No.1, pp. 33-49.

Strahler, A.N. 1964. Quantitative geomorphology of drainage basins and channel networks. In Handbook of Applied Hydrology, Ven te Cow, ed. McGraw-Hill, New York.

Stow, D.A. 1993. The role of geographic information systems for landscape ecological studies. In Landscape Ecology and GIS, R. Haines-Young, D.R. Green and S.H. Cousins,eds., Taylor and Francis, New York. pp. 11-21.

Sullivan, K, B. Black, C. Mahan, M. Abrams, K.C. Kim, and R. Yahner. 1998. Overstory Tree Composition of hemlock and hardwood stands. Report submitted to the National Park Service, Delaware Water Gap National Recreation Area, Milford, Pennsylvania.

Venables, W.N. and B.D. Ripley. 1994. Modern Applied Statistics with S-Plus. Springer-Verlag, New York. 462 pages.

Wilkinson, L. 1998. SYSTAT 8.0 Statistics (User Manual). SPSS, Inc. Chicago, Illinois.

USGS. 1993. US GeoData Digital Elevation Models: Data Users Guide. National Mapping Program Technical Instructions, Data Users Guide 5. US Geological Survey, Department of the Interior, Reston, Va. 48 pp.

Appendix 1-A.

Sample site locations:

Site # [1]	Stand[2]	Stream Name	Easting [3]	Northing [3]	Site Pair
042201	142	Shimers	518085.44	4573432.30	102211
051101	243	White Brook	517085.73	4571380.38	271111
072113	365	Conoshaugh	511424.98	4569959.43	222103
081102	529	Unnamed	513961.29	4567521.61	271112
083102	561	Unnamed	514157.01	4567332.15	273112
092112	485	Dry Brook	511492.68	4567552.97	152102
102211	657	Adams	510851.62	4565439.65	42201
111113	822	Dingmans	509375.98	4563553.52	271103
152102	1020	Unnamed	509338.23	4560689.94	92112
152213	1059	Hornbecks	507621.81	4559863.56	232203
162101	1202	Unnamed	508611.86	4558474.17	192111
172212	1191	Spackmans	507912.15	4557922.76	182202
182202	1327	Unnamed	507428.47	4556803.31	172212
191202	1335	Tumbling Waters	506283.37	4556880.46	291212
191211	1368	Tumbling Waters	506254.13	4556689.57	291201
192111	1449	Broadhead Cr.	506650.45	4555529.59	162101
222103	1784	Unnamed	502660.60	4551986.72	72113
232203	1850	Unnamed	500790.60	4551029.33	152213
271103	1909	Flat Brook tributary	504278.32	4549125.51	111113
271111	1509	Flat Brook tributary	510608.64	4554870.85	51101
271112	2037	Flat Brook tributary	503467.41	4549556.08	81102
273103	1614	Flat Brook tributary	510430.96	4554196.60	273113
273111	1673	Flat Brook tributary	509327.98	4553646.15	283101
273112	1653	Buttermilk Falls	510225.20	4553959.57	83102
273113	1742	Flat Brook tributary	507761.49	4552642.15	273103
283101	2204	Unnamed	503096.20	4547903.67	273111
291201	2035	Vancampens Brook	505862.37	4549032.81	191211
291212	2107	Vancampens Brook	505583.78	4548828.72	191202

[1] Site numbers were generated by USGS-BRD, are hierarchically structured, and represent stream drainage # (digits 1-2), terrain type (digit 3, 1=bench, 2=ravine, 3=mid-slope), stream order (digit 4), vegetation type (digit 5, hemlock =0, hardwood = 1), and replicate number (digit 6).

[2] Stand numbers were generated by USGS-BRD from polygon codes contained in vegetation map provided by Delaware Water Gap NRA personnel (Myers and Irish, 1981).

[3] Coordinates are expressed in Universal Transverse Mercator (UTM) format, Zone 18, using NAD27 geodetic datum.